Use of ultrasonic and electromagnetic NDT to evaluate durability monitoring parameters of concrete

Géraldine VILLAIN[1], Xavier DEROBERT[1], Odile ABRAHAM[1], Odile COFFEC[1], Olivier DURAND[1], Laurent LAGUERRE[1], Vincent BALTAZART[1]

[1] *LCPC, BP4129, 44341, Bouguenais cedex, France, geraldine.villain@lcpc.fr*

Abstract

In order to use nondestructive techniques (NDT) for the survey of reinforced concrete structures, it is important to show that they are able to measure the cover concrete characteristics related to its durability. For this purpose, various NDT were implemented to evaluate the mechanical and physical properties of concretes whose porosity is ranging from 12.5 to 18%. With regard to the mechanical waves, a technique founded on surface wave propagation detected by laser interferometry makes it possible to measure the phase velocity as a function of frequency, related to the concrete density and moduli. The results obtained are compared to those measured by impact echo. This method integrates the mechanical properties on all the thickness of the concrete slabs. With regard to the electromagnetic waves, the dielectric permittivity is measured from the slab surface by various capacitive probes and a multi-offset radar technique for evaluating the concrete water content between the surface and 5, 30 or 80 mm. The results obtained are compared to durability indicators (porosity) and durability monitoring parameters (water content and chloride content) as well as mechanical indicators (elastic modulus) emanating from destructive reference techniques.

Résumé

En vue d'utiliser les techniques non destructives (NDT) pour la surveillance des structures en béton armé, il est important de montrer que celles-ci peuvent mesurer les caractéristiques de durabilité du béton d'enrobage. Pour ce faire, différentes NDT ont été utilisées pour évaluer les propriétés mécaniques et physiques de bétons de porosité allant de 12.5 à 18%. En ce qui concerne les ondes mécaniques, une technique fondée sur la propagation d'ondes de surface détectées par interférométrie laser, permet de mesurer la vitesse de phase en fonction de la fréquence et de la relier à la densité et au module élastique. Les résultats obtenus sont comparés à ceux de l'impact-écho, une technique qui intègre les propriétés mécaniques sur toute l'épaisseur des dalles étudiées. En ce qui concerne les ondes électromagnétiques, la permittivité diélectrique est mesurée depuis la surface par différentes sondes capacitives et une technique radar multi-offset en évaluant la teneur en eau entre la surface et différentes profondeurs. Les résultats ND sont comparés à des indicateurs de durabilité (porosité) et des paramètres de suivi des dégradations (teneur en eau et en chlorure) comme à des indicateurs mécaniques (module élastique), tous mesurés par des techniques destructives de référence.

Keywords

Elastic modulus, porosity, water content, chloride ingress, concrete.

1 Introduction

As the part of the French national research project ANR-SENSO (2006-2008) aiming at a strategy of non destructive (ND) evaluation for the survey of the reinforced concrete structures, the involved researcher teams develop and apply various NDT on concrete slabs whose porosity and saturation degree are controlled in laboratory. This paper shows the results obtained by the five following techniques implemented by the LCPC team: impact-echo method, surface wave propagation, surface capacitive probes, multi-offset radar and step-frequency radar. The objective of the paper is to analyse the results with regards to the porosity *Φ* of the concretes, the static Young modulus E_{stat}, the water content *W* and the chloride content *[Cl]*. It is then shown that these techniques must be associated to evaluate the durability indicators and degradation monitoring parameters and, in the future, to estimate the potential durability of the concrete embedment of the reinforced concrete structures.

2 Experimental campaign

2.1 Characteristics of the concrete mixes and the concrete slabs

As the part of the project SENSO [1], nine concrete mixes were manufactured, mechanically characterized and tested by various nondestructive methods. In this paper, only six concretes were studied, named G1, G2, G3, G3a, G7 and G8, and mixed with the same cement, the same aggregates but with different water to cement ratios in order to have porosities ranging from 12 to 18%. The concrete G1 includes silica fume. Destructive tests are performed on cylindrical specimens or cores to characterize the concretes (Table 1).

Nondestructive measurements were carried out on nine slabs of 50x25x12 cm3 for each concrete at various degrees of saturation (0%, 40%, 60%, 80% and 100%). The dry state is reached by drying the samples in an oven at 80°C for a minimum of two months. The saturated state is obtained by immersion in water for 3 months approximately. Then, a part of the slabs (concretes G1, G3, G8) is partially saturated with a salt solution (30g/L or 120g/L) in a similar way, until they reach the water content expected.

Table 1. *Concrete characteristics in saturated conditions*

		G1	G2	G3	G3a	G7	G8
Water to cement ratio	W/C (-)	0,31	0,47	0,59	0,57	0,63	0,9
Compressive strength	Rc_{sat} (MPa)	72,9±1,4	43,3±0,8	43,8±1,5	40,5±0,7	38,3±0,8	20,2±1,0
Static deformation modulus	E_{sat} (GPa)	35,5±0,9	28,4±0,9	27,7±3,1	27,9±0,4	27,4±2,8	21,3±1,1
Mean density of the slab	ρ_{sat} (kg/m^3)	2441±8	2469±11	2457±13	2447±7	2455±12	2405±11
Porosity by water saturation	*Φ* (%)	12,5±0,3	14,3±0,2	15,5±0,5	16,0±0,7	15,9±0,8	18,1±1,0

2.2 ND testing methods

Different ND methods were used by the LCPC team to characterize concrete.

The **surface waves** (central frequency of 120 kHz) were used in order to determine the mechanical characteristics of material according to the depth. Thanks to a robot designed especially for the project, the laser interferometer moves on the axis of the slab upper face with a 5-mm step. The signal analysis allows the calculation of the phase velocity (V_φ) corresponding to the wavelength of 3 cm and a depth of about 1.5 to 2 cm [2,3]. This method makes it possible to access the gradients especially those due to skin effects.

The principle of the **impact-echo method** consists in a frequential analysis of mechanical waves propagating in a concrete structure following a shock of a steel ball [4]. For the survey of smaller slabs, the identification of frequencies corresponding to resonance or pseudo-stationary Lamb modes [5] allows to calculate the elastic Young modulus E_{dyn} and the Poisson ratio as well as the velocities of the compression and shear waves [6].

The principle of the **capacitive technique** rests on the resonance frequency measurement of an oscillating circuit (around 30-35 MHz) between two electrodes lying on the upper face of the concrete slab [7]. A calibration allows to obtain the concrete relative permittivity ε'_r, which is mainly related to the water content and the mixing components [8]. The volume investigated depends on the geometry of the electrodes (depth equal to 2-3mm for electrodes called PE, 2-3cm for ME, 8cm for GE). Thus for the large electrodes whose results are presented here, the concrete is auscultated on a 7-8 cm depth.

The last technique, presented in this paper, is the **radar using a bi-static antenna** (central frequency of 1.5 GHz), adapted to modify the offset between transmitter and receiver. By studying the arrival time of the direct wave, the relative permittivity ε'_r can be deduced. The investigated volume corresponds to a depth higher than 10 cm [7].

3 Analysis of the experimental results

3.1 Influence of porosity

Figure 1 presents some of the results obtained by mechanical (a and b) and electromagnetic (c and d) waves propagation against the porosity measured by water saturation for each concrete. Firstly, The tendency of the recorded dynamic elastic modulus E_{dyn} and surface wave velocities V_φ are in very good agreement, although the material depth involved is not the same. For the impact-echo method, E_{dyn} is deduced from the resonance frequencies of the 12-cm thick slabs, whereas the surface waves propagate in the first 2-3 centimetres of the slabs, where the skin effect modifies the properties of material. In both dry and saturated conditions, Fig. 1-a and 1.b show that the dynamic elastic modulus E_{dyn} and the surface wave velocities V_φ are very well correlated with the porosity of the concrete ($R^2=0.97$), in agreement with the results obtained by [9]. In the same way the results of mechanical wave propagation (corresponding to small deformations) are correlated linearly with the static Young modulus obtained in a destructive way on cylindrical specimens submitted to cyclic loadings (corresponding to great deformations) [3,5]. However, the static modulus is systematically lower than the dynamic modulus.

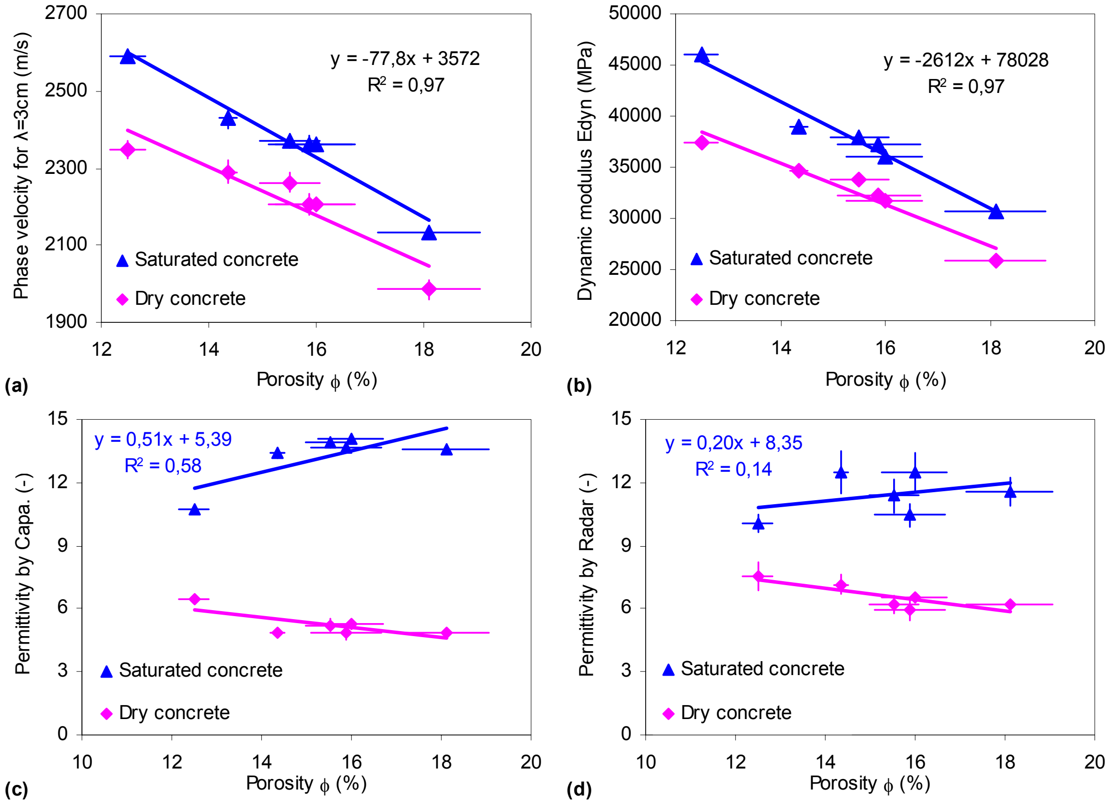

Figure 1. *Evolution with the porosity of 6 studied concretes: (a) Phase velocity corresponding to 3-cm wave length (LASER device) – (b) Dynamic elastic modulus (impact-echo) – (c) Dielectric permittivity (capacitive method) – (d) Dielectric permittivity (Radar)*

Secondly, the tendencies of the relative dielectric permittivities ε'_r obtained by the multi-offset radar (1-c) and capacitive probes (1-d) are also in good agreement together but very slightly correlated with the concrete porosity. Meanwhile they are influenced by porosity and it has to be taken into account for concrete diagnosis.

3.2 Influence of water content

As shown above, the methods based on the propagation of mechanical waves (Fig. 2-a and 2-b), in one hand, and on electromagnetic waves (Fig. 2-c and 2-d), in the other hand, give respectively concordant results, correlated with the volumetric water content *W* of the concrete slabs. All the curves obtained for G1 evolves differently according to *W* from those of the other formulations. Indeed, the concrete G1, of weak *W/C* and containing silica fume, has a finer micro-structure than the other concretes thus its degree of saturation is more difficult to control, moreover the relative dielectric permittivities ε_r is influenced by the mix components.

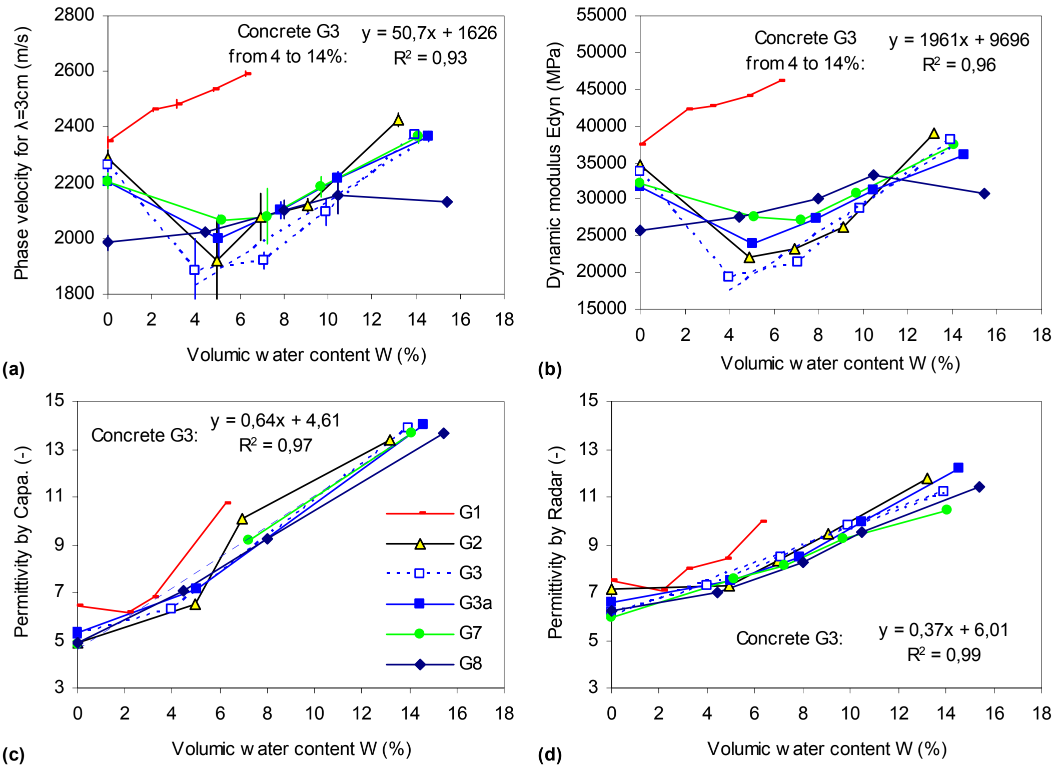

Figure 2. *Evolution with the water content W of 6 concrete studied: (a) Phase velocity corresponding to 3-cm wave length (LASER device) – (b) Dynamic elastic modulus (impact-echo) – (c) Dielectric permittivity (capacitive method) – (d) Dielectric permittivity (Radar)*

Measurements by propagation of mechanical waves are influenced by *W* as previously shown by [9,10]. For *W* ranging between 4% and 14% approximately (rate of saturation $40\%<S<100\%$), the surface wave velocity and the dynamic modulus increase linearly with *W*. Otherwise, for very low saturation degree ($W<4\%$), the velocity V_φ decreases up to a minimum value because of increase in density for the concretes G2, G3, G3a and G7. This phenomenon was observed for the compression and shear waves in sands and sandstones [11] and in limestone [12], and is explained by capillary strength which increases at very low water content. This phenomenon was not observed in cementitious materials [9,10], because the water content corresponding to a minimal velocity was neither reached nor studied.

The permittivities ε'_r obtained by the electromagnetic methods are linearly correlated with the volumetric water content (*W*), for concretes formulated with the same aggregates and same cement, in agreement with [13,14], excepted for the results at 0% when the slabs were not completely dry. As the correlation coefficients are very high ($R^2>0.97$), it could be possible to predict the water content thanks to electromagnetic methods, once the concrete mix is known. Besides, the measurements carried out with capacitive electrodes of various sizes must make it possible to evaluate the gradients of water content according to the depth [7]. Moreover, this figure confirms that the influence of the porosity do not appear clearly on the results.

3.3 Influence of chloride content

Figure 3 shows the permittivities measured for two different chloride concentrations ([NaCl]=30g/L and 120g/L) against the water content. The results obtained by mechanical wave propagation are not sensitive to the chloride content thus are not shown. The more the [NaCl] increases, the more the permittitivities increase, however in a less important way than expected following the results obtained by the same authors on different concretes saturated under vacuum with 30 and 120g/L salt solutions [8]. That can be explained by the experimental protocol used for the chloride ingress. The problem is that the chloride content is not homogeneous in the 12-cm thick slabs, that there is a chloride gradient and that, close to the surface, the internal concentration increases with the duration of immersion (see Table 2). This protocol explains the results of permittivity and must be studied more carefully to be able to measure the gradients in further research.

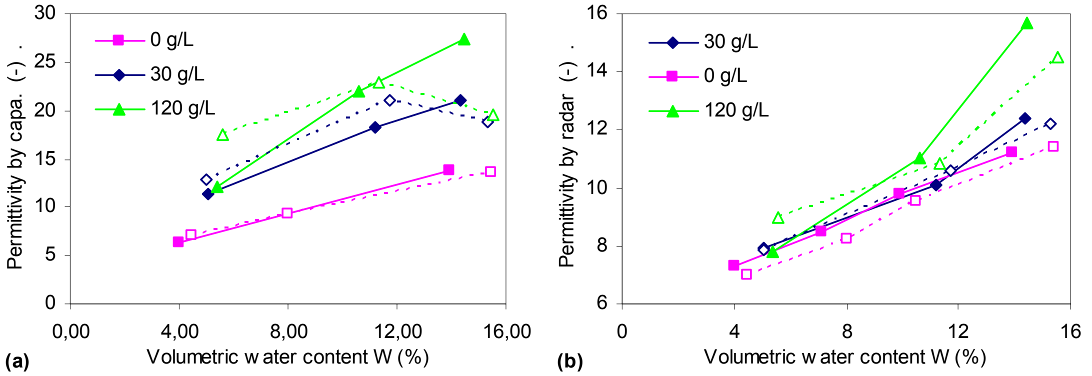

Figure 3. *Evolution with the chloride content of 2 concrete (dashed curve for G3 and full curve for G8): Dielectric permittivity by (a) capacitive method – (b) Radar*

Table 2. *Chloride profiles (chloride mass for 100g of dry concrete) at different saturation degrees (concretes G3 and G8)*

Depth	G3 – 30 g/L			G3 – 120 g/L			G8 – 30 g/L			G8 – 120 g/L		
	S(%) 40	S(%) 80	S(%) 100	S(%) 40	S(%) 80	S(%) 100	S(%) 40	S(%) 80	S(%) 100	S(%) 40	S(%) 80	S(%) 100
5 mm	0.05	0.24	0.21	0.19	0.46	0.42	0.08	0.11	0.14	0.34	0.26	0.39
10 mm	0.06	0.10	0.20	0.16	0.27	0.35	0.07	0.11	0.08	0.31	0.22	0.34
15 mm	0.06	0.06	0.18	0.14	0.23	0.35	0.06	0.11	0.07	0.25	0.21	0.34
20 mm	0.06	0.09	0.14	0.13	0.20	0.36	0.04	0.11	0.08	0.24	0.23	0.32

4 Conclusions

The results presented in this paper show that ND measurements by propagation of mechanical and electromagnetic waves are complementary. The mechanical waves, influenced by the water content, make it possible to evaluate the mechanical properties such as porosity and the elastic modulus corresponding to great deformations. However, a higher degree of accuracy would be obtained if the effect of the water content could be taken into account. Moreover, the nonlinear effect of the water content observed on the phase velocity and on the dynamic modulus could be explained by capillary effects at low saturation degree.

The electromagnetic waves, influenced slightly by the porosity and also by the nature of the components (i.e. silica fume for *G1*), provide permittivities linearly correlated with the water content. Under the hypothesis of knowing a reference state of a studied material, it will be then possible to determine the water content depending on the external thermo-hygrometric exposure. The permittivities obtained are particularly sensitive to chloride content contrary to mechanical waves, but further work has to be done on this effect.

As a conclusion, the different NDT are considered here as of complementary use in the assessment of cover concrete durability indicators and monitoring parameters.

Acknowledgements

The French National Research Agency is gratefully acknowledged for the support of the ANR-SENSO project.

References

1. Balayssac, J-P., Laurens, S., Arliguie, G., Ploix, M.A., Breysse, D., Piwakowski, B., Dérobert, X. (2009) "SENSO, a French project for the evaluation of concrete structures condition by combining non destructive testing methods", *NDT Conf. on Civil Engineering*, Nantes, France, 30 june-3 july 2009, 6.

2. Bodet, L., van Wijk, K., Bitri, A., Abraham, O., Côte, P., Grandjean, G., and Leparoux, D. (2005) "Surface-wave dispersion inversion limitations from laser-Doppler experiments", *Journal of Environmental & Engineering Geophysics*, Vol. 10, issue 2, pp.151-162.

3. Abraham, O., Villain, G., Lu, L., Cottineau, L-M., Durand, O. (2009) "A laser interferometer robot for the study of surface wave sensitivity to various concrete mixes", *NDT Conference on Civil Engineering*, Nantes, France, 30 june-3 july 2009, 6p.

4. Sansalone M.J., Streett W.B. (1997) "Impact echo: non-destructive evaluation of concrete and masonry", Bullbrier Press.

5. Villain, G., Abraham, O., Le Marrec, L., Rakotomanana, L. (2009) "Determination of the bulk elastic moduli of various concrete by resonance frequency analysis of slabs submitted to degradations", *NDT Conf. on Civil Engineering*, Nantes, France, 30 june-3 july 2009, 6p.

6. Gibson A, Popovics J. (2005) "Lamb wave basis for impact-Echo method analysis", *Journal of Engineering mechanics*, april 2005, pp.438-443.

7. Dérobert, X., Iaquinta, J., Klysz, G., Balayssac, J.P. (2008) "Use of capacitive and GPR techniques for non-destructive evaluation of cover concrete", *NDT&E International*, Vol. 41, pp.44-52.

8. Dérobert, X., Villain, G., Cortas, R., Chazelas JL. (2009) " EM characterization of hydraulic concretes in the GPR frequencyband using a quadratic experimental design", *NDT Conference on Civil Engineering*, Nantes, France, 30 june-3 july 2009, 6 p.

9. Lafhaj, Z., Goueygou, M., Djerbi, A., Kaczmarek, M. (2006) "Correlation between porosity, permeability and ultrasonic parameters of mortar with variable water / cement ratio and water content", *Cement and Concrete Research*, Vol. 36, Issue 4, pp.625-633.

10. Ohdaira, E., Masuzawa, N. (2000) "Water content and its effect on ultrasound propagation in concrete - the possibility of NDE", *Ultrasonics*, Vol. 38 (1-8), pp.546-552.

11. Murphy, W. M. (1982) "Effects of partial water saturation on attenuation in Massilon sandstone and Vycor porous glass", *J. Acoustical Society of America*, Vol. 71, Issue 6, pp.1458-1468.

12. Homand, F., Duffaut, P. (2000) "Manuel de mécanique des roches - 1-fondements", Comité français de mécanique des roches, Presses de l'Ecole des Mines de Paris, 267p.

13. Soutsos, M. N., Bungey, J. H., Millard, S. G., Shaw, M. R., Patterson, A. (2001) "Dielectric properties of concrete and their influence on radar testing", *NDT & E International*, Vol. 34, Issue 6, pp.419-425.

14. Klysz, G., Balayssac, J.-P. (2007) "Determination of volumetric water content of concrete using ground-penetrating radar", *Cement and Concrete Research*, Vol. 37, Issue 8, pp.1164-1171.